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MEASUREMENT OF SOLAR RADIATION AT THE EARTH'S SURFACE

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DEPARTMENT OF ENERGY SOLAR ENERGY METEOROLOGICAL RESEARCH AND TRAINING SITES (SEMRTS)

Eight universities have received grants from the U.S. Department of Energy (DOE) to establish Solar Energy Meteorological Research and Training Sites (SEMRTS). Under this SEMRTS program each of the universities selected will have the responsibility of carrying out a 5-year program of solar radiation measurements and establishing solar energy training courses in regular and special-educational programs at the university.

The eight universities selected are: University of Alaska, University of California at Davis, Georgia Institute of Technology, University of Hawaii, University of Michigan, State University of New York, Oregon State University, and Trinity University.

The regions of the United States for which each university has responsibility for a SEMRTS program are shown in figure 1. The University of Michigan has the responsibility for region 6, the Great Lakes States region, including the following states: North Dakota, South Dakota, Nebraska, Minnesota, Iowa, Wisconsin, Illinois, Indiana, Ohio, and Michigan. The measurement programs were begun October 1, 1977, and are expected to last through September 31, 1982.

The objective of this discussion is to provide a background of information regarding the characteristics of solar energy arriving at the Earth's surface. This will enable an understanding of the nature of the measurements being made. First we will look briefly at the history of the measurement of surface solar radiation in the United States. After this, characteristics of the SEMRTS measurement program will be described, and some of the interesting characteristics of solar energy measurements already made, as selected from the literature, will be presented.

DEFINITIONS: SOLAR RADIATION CHARACTERISTICS

The nature of solar radiation as it arrives at the top of the Earth's atmosphere and its modification through interaction with the Earth's atmosphere and clouds are discussed in many textbooks on meteorology and physical climatology. All aspects of this topic are discussed in the course notes for the University of Michigan College of Engineering Intensive Summer Conference Short Course, which was last held in Ann Arbor on July 9-10, 1979. (These notes

provided much of the background material for this presentation. In particular, the brief outline of the history of solar radiation measurements contained herein is based on material assembled by Associate Professor Dennis G. Baker.)

Solar Radiation Outside the Earth's Atmosphere

The amount of solar radiant energy arriving per unit time at a unit area of surface at the top of the Earth's atmosphere normal to the beam of radiation from the Sun, at the mean Earth-Sun distance, is called the solar constant. At this date it is thought to be 1367 W/m^2 (Hickey, 1978), or, in other commonly used units, 1.96 cal cm^{-2} min^{-1}. The spectral distribution of the solar radiation arriving at the top of the Earth's atmosphere in the UV, visible, and near-IR portions of the spectrum is shown in figure 2 compared with the amount of solar spectral flux density that would arrive at that point if the Sun radiated as a 5000-K, 5800-K, or 6000-K blackbody. The fraction of the solar constant which lies in three major wavelength bands is as follows:

Wavelength range, μm	0-0.38	0.38-0.78	0.78-∞
Fraction in range	0.0700	0.4729	0.4571

A much more detailed breakdown of the solar flux outside the Earth's atmosphere is given in table I.

The flux of solar radiation arriving at the Earth varies inversely as the square of the Earth-Sun distance. The annual variation of the solar flux during the course of a year as the Earth moves in its elliptical orbit is given in table II.

A quantity of interest for meteorological and climatological purposes is the total daily solar radiation arriving at a horizontal surface outside the Earth's atmosphere at an arbitrary latitude b. This quantity can be calculated from the equation

$$E_D = H_S R_{ES}^2 \int_{t_1}^{t_2} \frac{\cos \theta_o}{r_{ES}^2} dt \qquad (1)$$

where

E_D	total daily solar radiation on a horizontal plane
H_S	solar constant
R_{ES}^2	square of the mean Earth-Sun distance
r_{ES}^2	square of the Earth-Sun distance on the day of concern

θ_o zenith angle of the Sun

t_1, t_2 time of sunrise and sunset, respectively

The zenith angle of the Sun can be calculated from

$$\cos \theta = \sin b \sin \delta_s + \cos b \cos \delta_s \cos h_s \tag{2}$$

where

b latitude of the point on the surface of the Earth for which the calculation is made

δ_s declination angle of the Sun

h_s Sun's hour angle, which varies during the day

The results of the integration of equation (1) for each day of the year and all latitudes are shown in figure 3.

Effect of Earth's Atmosphere on Solar Radiation

The beam of direct radiation from the Sun is attenuated as it passes through the Earth's atmosphere by absorption by some of the minor gaseous constituents of the Earth's atmosphere, by Rayleigh scattering by the gaseous molecules of the Earth's atmosphere, and by Mie scattering and absorption by aerosols in the Earth's atmosphere. The atmospheric gases having the greatest effect in absorbing solar energy are ozone (O_3), carbon dioxide (CO_2), and water vapor (H_2O).

With suitable modeling, the effect of the above factors on the radiation in the direct beam of the Sun is as illustrated in figure 4, which shows the results of such a calculation by Gates (1966). This figure shows the spectral distribution of the radiation arriving at the Earth's surface in the direct beam of the Sun under clear sky conditions and with normal amounts of O_3 and CO_2 and rather small amounts of H_2O and aerosols in the atmosphere. Figure 5 shows the results of a similar calculation where the amounts of radiation absorbed and scattered out of the direct beam of the Sun by the various factors are identified (Paltridge and Platt, 1976).

The amount of H_2O and aerosols in the Earth's atmosphere is highly variable. The effect of this on the Earth's solar radiation is described by a quantity called the turbidity. This phenomenon has been studied with the aim of defining a parameter which can be evaluated by measurements of direct solar radiation. The Angstrom (1961) turbidity coefficient β is defined by the equation

$$\tau_\lambda = \beta\lambda^{-\alpha} \tag{3}$$

Measurements have shown that an average value of α is 1.3. For simplicity, then, one can use the equation

$$\tau_\lambda = \beta\lambda^{-1.3} \tag{4}$$

to provide a measurement of the amount of aerosol in the atmosphere. Using a filter at a wavelength of 0.5 µm, where water vapor has a negligible absorbing effect, the extinction τ_λ can be measured and β can be calculated. Volz (1969) has defined the turbidity coefficient in a somewhat similar fashion. His factor is 1.069 times that of Angstrom. Average values for July and December for the 13-year period from 1961 to 1974 are given in figures 6 and 7 (Flowers et al., 1969). The Volz turbidity coefficient is used in these figures. (Note that the average turbidity is significantly higher in the eastern part of the United States.)

The scattering of solar radiation by the air molecules and aerosols in the atmosphere results in the skylight which arrives at the Earth from all directions. Rayleigh scattering is greater in the forward and backward directions, but has a considerable amount of scattering in the sidewise direction. Aerosol scattering is mainly in the forward direction. The net result is that there is a large amount of scattering in the forward direction, as shown in figure 8. The scattering effects are wavelength dependent; however, the features shown in the figure appear in the skylight intensity to some extent at all wavelengths.

Solar Radiation Quantities Measured at Earth's Surface

The spatial distribution of the solar radiation arriving at the surface of the Earth and the instruments which are used to measure the several kinds of solar radiation are shown schematically in figure 9. The direct solar radiation (i.e., the almost-parallel beam of radiation) plus some of the circumsolar radiation (i.e., a portion of the quite intense forward-scattered radiation) is measured by a pyrheliometer, which tracks the Sun from sunrise until sunset. The global radiation (i.e., all of the radiation arriving on a horizontal surface from the hemispherical dome of the sky) is measured by an instrument called a pyranometer. The diffuse radiation from the sky, not including the direct plus circumsolar radiation, is measured by a pyranometer with a shadow band which is adjusted to keep the direct beam from arriving at the detector at all times as the Sun passes in its daily arc across the sky. A pyranometer with an occulting disk which tracks the Sun can also be used. When a shadow band is used, a portion of the diffuse radiation from the sky is also prevented from reaching the detector. A correction must be made for this effect. The occulting disk, if designed and operated properly, would normally not need a correction factor.

Each of these three measurements can be made with a spectral response which covers almost all of the spectral range of solar radiation arriving at the surface. In practice, the wavelength range measured is from 0.28 to 2.8 µm

(clear glass) or from 0.29 to 4.5 μm (quartz). Additional measurements are made with filters. The details of the filter measurements will be noted subsequently in this report.

The global downcoming infrared radiation from the sky in the spectral range of 4 to 50 μm is also measured by a pyranometer-type instrument called a pyrgeometer. The ultraviolet radiation from the hemisphere of the sky in the spectral range 0.285 to 0.385 μm is measured with a UV radiometer (photometer). Another instrument used is a Campbell-Stokes sunshine recorder, which measures the duration instead of the intensity of the solar radiation. It consists of a spherical glass ball which focuses the Sun's rays onto the heat-sensitive surface of a card which is fastened into a spherical card holder. The focused Sun's rays burn a narrow track onto the card when the intensity of the direct beam of the Sun is greater than 0.1 to 0.2 of the solar constant. A time scale on the card enables the determination of the duration of sunshine in hours and tenths of hours.

Atmospheric turbidity is measured quite conveniently with a Volz sun-photometer, a compact instrument with appropriate filters, optics, and detector. It is hand held, and readings can usually be taken in less than a minute. The turbidity is then calculated. More details on the solar energy measurements at the University of Michigan are given subsequently in this report.

BRIEF HISTORY OF SOLAR ENERGY MEASUREMENTS IN THE U.S.

This historical outline of solar radiation measurements in the United States considers those data which have been archived at the National Climatic Center in Asheville, N.C. Other data, taken by individuals, private organizations, universities, and government laboratories, which have not been archived at the National Climatic Center are not discussed.

Direct solar radiation measurements were taken as far back as 1902 at Asheville, N.C. The network of normal-incidence measurements of direct solar radiation then slowly expanded, as shown in figure 10. Global solar radiation measurements were begun in 1906. The network of global solar radiation measurement stations developed slowly. The network locations as of 1939 are shown in figure 11. The network was cut back during World War II, but by 1950 it had increased to 83 stations (fig. 12), and by 1972 90 sites were regularly reporting data (fig. 13).

Problems with the global radiation measurements developed because of inadequate calibration procedures and also because of deterioration of a Parson's black paint used on the detectors of some pyranometers. The accuracy of the data in the network became questionable in the 1960's. Since 1972, data from only a limited number of 28 stations using the Eppley Precision Spectral Pyranometer (PSP) have been approved for publication. As a result of these problems, it was decided to start anew in building up a network with modern equipment. The new network is shown in figure 14. The locations of some of the DOE SEMRTS stations are also shown in this figure.

The data for the period of problem measurements have been rehabilitated and augmented. Rehabilitation was accomplished by the procedure of examining data for clear days under the assumption that there were no trends in the data. Three models were developed as follows: (1) standard year clear solar noon, (2) total horizontal solar radiation model, and (3) direct normal solar radiation model. The models were used to correct and fill in data gaps and to add direct normal values at the stations indicated in figure 15.

MEASUREMENTS AT UNIV. OF MICHIGAN AND OTHER SEMRTS SITES

The measurements being made at all SEMRTS sites are indicated in the specifications given in tables III, IV, and V. Radiation measurements are listed in table III, meteorological measurements appear in table IV, and calibration procedures are given in table V. These specifications may be changed slightly in some detail, but for the most part they are being adhered to at the SEMRTS stations.

Measurements at Univ. of Michigan Primary Site

Various radiation measurements are being made at the University of Michigan primary site on the roof of the Space Research Building. Global solar radiation on a horizontal plane is being measured by an Eppley Precision Spectral Pyranometer. A clear glass dome with a wavelength response of 0.285 to 2.8 μm is being used. Measurements are also made on occasion with the following filter domes: yellow (GG14), 0.5 to 2.8 μm; orange (OG1), 0.525 to 2.8 μm; red (RG2), 0.63 to 2.8 μm; and dark red (RG8), 0.71 to 2.7 μm. Diffuse measurements are made with an Eppley PSP with a clear glass dome and an occulting disk. Measurements are also made with an Eppley PSP tilted to the south at an angle from the zenith equal to the latitude of the station. A clear glass dome is used and the instrument is shielded so that it does not receive reflected radiation from the Earth.

Global ultraviolet radiation is measured with an Eppley UV Radiometer in the spectral range from 0.295 to 0.385 μm, and global infrared radiation is measured with an Eppley Infrared Radiometer (pyrgeometer) with a wavelength response of 4 to 50 μm. There are also plans to bring into operation a Funk total hemispherical radiometer, which will measure in the range from 0.2 to 60 μm. Measurements are also made with the Campbell-Stokes sunshine recorder (duration of sunlight) and with the Volz sunphotometer (turbidity). Photographs of the site and of some of the instruments used for the solar energy measurements are shown in figures 16 through 20. The recording station and mobile solar energy measurement facility are shown in figures 21 and 22, respectively.

Measurements With Mobile Univ. of Michigan Solar Energy Facility and at Other Locations in Great Lakes States Area

The mobile measurement facility shown in figure 22 contains two Eppley Precision Spectral Pyranometers, which measure direct plus diffuse solar

radiation on a horizontal surface in the 0.28- to 2.8-μm spectral region and in four narrower spectral regions: 0.5 to 2.8 μm, 0.53 to 2.8 μm, 0.63 to 2.8 μm, and 0.7 to 2.8 μm. Another Eppley PSP measures direct plus diffuse solar radiation on a plane surface which can be inclined at various angles. An Eppley Normal Incidence Pyrheliometer (NIP) with a solar tracker measures the direct component of solar radiation. The facility has a collapsible meteorological tower for measurements of wind speed, wind direction, temperature, and dew point at heights up to 10 m. Measurements have been made with the mobile facility at Jordan College in Michigan, Iron Mountain, Mich., and Burlington, Vt.

Three secondary stations have been established at sites in the Great Lakes States area where long-term hourly data exist; i.e., Omaha, Neb.; Madison, Wis.; and the Argonne National Laboratory in Lemont, Ill. Each of these stations contains an Eppley PSP inclined at an angle equal to the station's latitude, along with an array of recording devices.

CHARACTERISTICS OF SOLAR RADIATION ARRIVING AT THE EARTH'S SURFACE

Figure 23 shows the annual variation of daily solar radiation arriving at the surface on cloudless days at Ann Arbor. These measurements were made at the University of Michigan primary site. The curves show direct radiation on a plane normal to the Sun's rays, global radiation on a horizontal plane, global radiation on a plane tilted by 42.3°, global radiation on a horizontal plane with a 0.63- to 2.8-μm filter, diffuse radiation on a horizontal plane, and ultraviolet radiation on a horizontal plane.

A typical curve of direct normal, total (global) horizontal, and diffuse horizontal radiation (fig. 24) shows the variation in these quantities from sunrise to sunset on a clear day. These measurements should satisfy the following equation at any time of the day:

$$\text{total (global)} = \text{direct} \cos \theta + \text{diffuse}$$

where θ is the solar zenith angle. The data shown in this figure are for Albuquerque, N.M.

Since not all days are clear, however, the direct solar radiation is often much less than that shown in figure 24. Direct normal solar radiation for Albuquerque is shown in figure 25 for the 31 days of January 1962. The daily totals of direct normal solar radiation for each day for a 4-year period at Albuquerque are shown in figure 26. The top curve shows the maximum available direct normal solar radiation. The curve of the average value shows that at Albuquerque the amount of direct normal solar radiation is, on the average, about 75 percent of the maximum possible. In contrast, the average amount of direct normal solar radiation at Maynard, Mass., is about 50 percent of the maximum possible (fig. 27).

Average measured global solar radiation on a horizontal surface is shown in figure 28 for the period of 1 year for four locations under three different

sky conditions (clear skies, 50-percent cloud cover, and 100-percent cloud cover). In each case the solar radiation at the top of the atmosphere is shown for comparison. Note that the decrease in solar radiation in going from clear sky to 50-percent cloud cover is much less than the decrease in going from 50-percent to 100-percent cloud cover.

Figures 29 and 30 show the distribution over the United States, in May, of mean daily direct solar radiation and mean daily global solar radiation on a horizontal surface (Lester Machta, Air Resources Laboratory, NOAA, private communication, 1979). The superiority of the southwest part of the U.S. for solar energy applications is obvious.

The effects of turbidity on the direct and circumsolar radiation are shown in figure 31. On a clear day with low turbidity, with the circumsolar radiation equal to 1 percent of the direct normal measured value, the intensity toward the center of the Sun is great and the diameter of the Sun is well defined. When the turbidity is high, with the circumsolar radiation equal to 25.6 percent of the direct normal value, the intensity toward the center of the Sun is much lower, the diameter of the Sun is not as well defined, and it appears to be smaller than normal.

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TABLE I.- SOLAR FLUX ABOVE THE EARTH'S ATMOSPHERE

[From Thekaekara, 1974]

λ^*	$E_\lambda{}^*$	$D_\lambda{}^*$	λ	E_λ	D_λ	λ	E_λ	D_λ
0.115	0.007	1×10^{-4}	0.43	1639	12.47	0.90	891	63.37
0.14	0.03	5×10^{-4}	0.44	1810	13.73	1.00	748	69.49
0.16	0.23	6×10^{-4}	0.45	2006	15.14	1.2	485	78.40
0.18	1.25	1.6×10^{-3}	0.46	2066	16.65	1.4	337	84.33
0.20	10.7	8.1×10^{-3}	0.47	2033	18.17	1.6	245	88.61
0.22	57.5	0.05	0.48	2074	19.68	1.8	159	91.59
0.23	66.7	0.10	0.49	1950	21.15	2.0	103	93.49
0.24	63.0	0.14	0.50	1942	22.60	2.2	79	94.83
0.25	70.9	0.19	0.51	1882	24.01	2.4	62	95.86
0.26	130	0.27	0.52	1833	25.38	2.6	48	96.67
0.27	232	0.41	0.53	1842	26.74	2.8	39	97.31
0.28	222	0.56	0.54	1783	28.08	3.0	31	97.83
0.29	482	0.81	0.55	1725	29.38	3.2	22.6	98.22
0.30	514	1.21	0.56	1695	30.65	3.4	16.6	98.50
0.31	689	1.66	0.57	1712	31.91	3.6	13.5	98.72
0.32	830	2.22	0.58	1715	33.18	3.8	11.1	98.91
0.33	1059	2.93	0.59	1700	34.44	4.0	9.5	99.06
0.34	1074	3.72	0.60	1666	35.68	4.5	5.9	99.34
0.35	1093	4.52	0.62	1602	38.10	5.0	3.8	99.51
0.36	1068	5.32	0.64	1544	40.42	6.0	1.8	99.72
0.37	1181	6.15	0.66	1486	42.66	7.0	1.0	99.82
0.38	1120	7.00	0.68	1427	44.81	8.0	0.59	99.88
0.39	1098	7.82	0.70	1369	46.88	10.0	0.24	99.94
0.40	1429	8.73	0.72	1314	48.86	15.0	4.8×10^{-2}	99.98
0.41	1751	9.92	0.75	1235	51.69	20.0	1.5×10^{-2}	99.99
0.42	1747	11.22	0.80	1109	56.02	50.0	3.9×10^{-4}	100.00

$^*\lambda$ wavelength, μm

E_λ solar spectral irradiance, $W/m^2\ \mu m^{-1}$, averaged over small bandwidth centered at λ

D_λ percentage of solar constant associated with wavelengths shorter than λ

TABLE II.- ANNUAL VARIATION OF SOLAR FLUX

DUE TO ORBITAL ECCENTRICITY

[From Meinel and Meinel, 1977]

Date	Departure from mean	Solar flux, kW/m^2
Jan. 1	1.0342	1.438
Feb. 1	1.0296	1.431
Mar. 1	1.0181	1.415
Apr. 1	1.0016	1.392
May 1	0.9848	1.369
June 1	0.9721	1.351
July 1	0.9673	1.345
Aug. 1	0.9716	1.350
Sept. 1	0.9835	1.367
Oct. 1	1.0003	1.390
Nov. 1	1.0172	1.414
Dec. 1	1.0296	1.431

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TABLE III.- RADIATION MEASUREMENTS AT SOLAR ENERGY METEOROLOGICAL RESEARCH AND TRAINING SITES

Type of measurement	Instrument	Procedure	Sampling	Comments
Basic[a]:				
Global (WG7)	Eppley PSP	NOAA[b] + frost/dew prevention	1 minute + hourly (SOLMET)	SERI and NOAA coordinate purchase
Diffuse (WG7)	Eppley PSP - shadow band or tracking , disk	NOAA[b] + frost/dew prevention	1 minute + hourly (SOLMET)	SERI and NOAA check disk
Direct (WG7)	Eppley NIP + tracker	NOAA	1 minute + hourly (SOLMET)	SERI and NOAA coordinate purchase
Downward infrared (long & short)	CSIRO[c], Funk-type Sci. Associates Model 822	NOAA	1 minute + hourly (SOLMET)	SERI and NOAA coordinate purchase
Total (WG7) on surface tilted at latitude, pointed south	Eppley PSP	NOAA + document instrument view with fisheye photo; frost/ dew prevention	1 minute + hourly (SOLMET)	SERI and NOAA coordinate purchase
Global (RG2)	Eppley PSP	NOAA + frost/dew prevention	1 minute + hourly (SOLMET)	SERI and NOAA coordinate purchase
Global (UV)	Eppley UV photometer	NOAA	1 minute + hourly (SOLMET)	SERI and NOAA coordinate purchase
Research[d]:				
Global, diffuse, direct (OG1, RG2, & RG8 filters)	Eppley PSP's + NIP	NOAA + IGY + WMO + frost/dew prevention	Interval determined by NIP filter wheel; hourly - SOLMET	SERI and NOAA coordinate purchase
Photovoltaic - horizontal lat., lat. + 10°, lat. - 10° (south)	Standard cells - JPL & NASA	JPL & NASA	1 minute + hourly (SOLMET)	SERI and NOAA to check with JPL and NASA Coordinate purchase
Total (WG7) on lat., lat. + 10°, lat. - 10°, vertical, at four cardinal points	Eppley PSP	NOAA + measure ground albedo + frost/dew pre- vention + document (photo) view	1 minute + hourly (SOLMET)	SERI and NOAA coordinate purchase
All of the above for spectral scans (bands), narrow fields of view	Specified by PI	Specified by PI	Specified by PI	Includes circumsolar

[a]Measurements will be archived at Solar Energy Research Institute (SERI), Golden, Colorado.
[b]NOAA network, plus annual photos of site (pyranometer FOV), using local standard time.
[c]Commonwealth Scientific Industrial and Research Organization.
[d]Data used by SEMRTS personnel.

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TABLE IV.- METEOROLOGICAL MEASUREMENTS AT SOLAR ENERGY METEOROLOGICAL RESEARCH AND TRAINING SITES

Type of measurement	Instrument	Procedure	Sampling	Comments
Basic:				
Temperature Dew point Wind speed and direction Pressure Precipitation	Optional: PI's should coordinate with each other concerning their specific instrumentation and calibration	WMO and NWS	1 min + hourly (SOLMET)	Use best possible exposure
Cloud cover	NA	NWS	Hourly	Obtain from NWS
Percent sunshine	Campbell Stokes	WMO and IGY	Daily/hourly	
Present weather	NA	NWS	Hourly	
Research:				
Cloud cover	PI specified	PI specified	PI specified	May use satellite fisheye camera
Visibility	Observation (human) Nephelometer Contrast photometer, photograph	WHO and NWS	PI specified	
Turbidity	Volz photometer PI specified	WMO and IGY	PI specified	
Others:				
Total ozone, NO_x, CO, O_3, etc., particulates, precip. H_2O, cloud height, and altitude profiles of above	PI specified	PI specified	PI specified	PI's to report May 1978

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TABLE V.- CALIBRATION PROCEDURES AT SOLAR ENERGY METEOROLOGICAL RESEARCH AND TRAINING SITES[a]

Calibration of -	Instrument	Procedure	Sampling	Comments
Station log	NA	NOAA network		-
Pyrheliometers & pyranometers	Each PI maintain at least one reference	PI reference instrument traceable to NOAA (Boulder), traveling standard (NOAA) to be considered, calibration technique of NOAA	Annual	PI may want to purchase own instrument PACRAD[b] primary standard radiometer
Funk infrared radiometer	CSIRO	Conduct joint calibration/ comparison with all PI's; Trinity University to maintain traveling std.	Annual	SERI to maintain and establish standard and technique
UV photometer	Eppley photometer	Conduct joint calibration/ comparison with all PI's; Univ. of Cal. to maintain traveling std.	Annual	SERI and UC (Davis) will maintain standard and technique
Meteorological	-	WMO	As required	
Electronics	-	Common electrical standards and traceability to primary and secondary units	As required	Recommend back-up strip chart recorder(s) be used for quality control
Electromagnetic interference	-	PI to provide documentation and some measurement of electromagnetic interference environment and its impact on measurements	As required	

[a]PI's will deliver quality-controlled 1-minute data 30 working days after end of each month of data collected. Short-term data (less than 30 days) to be provided in publication form.

[b]Precision Active-Cavity Radiometer.

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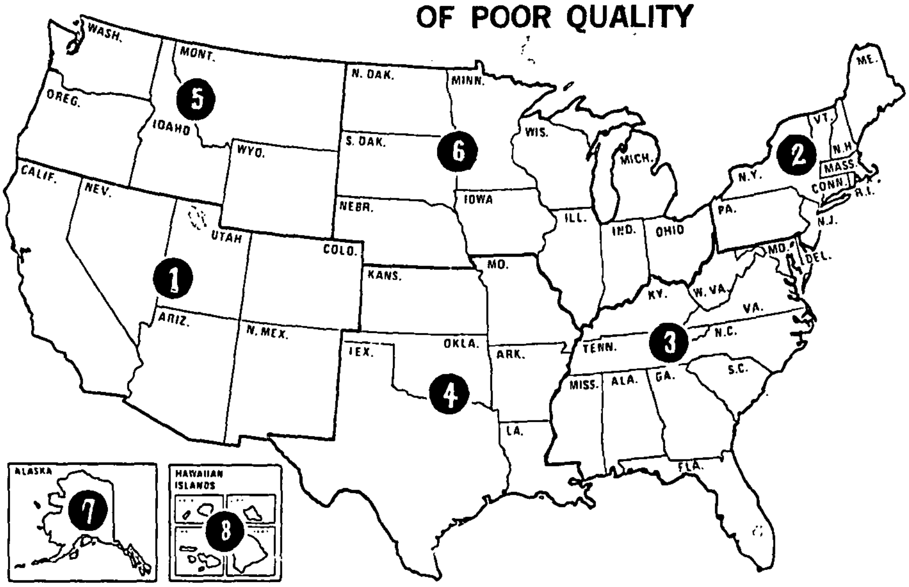


Figure 1.- Regions for Solar Energy Meteorological Research and Training Sites.

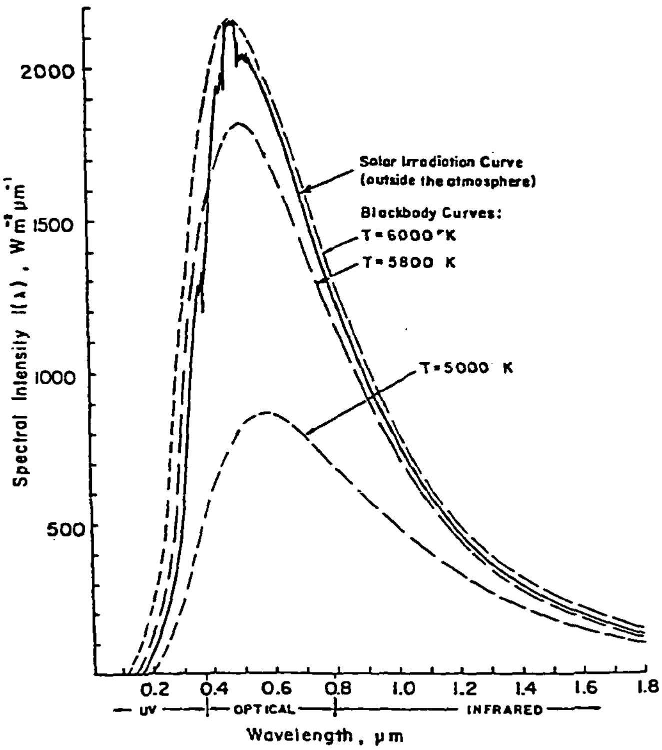


Figure 2.- Solar spectral irradiance at Earth's mean orbital distance compared to blackbody curves for 5000 K, 5800 K, and 6000 K.

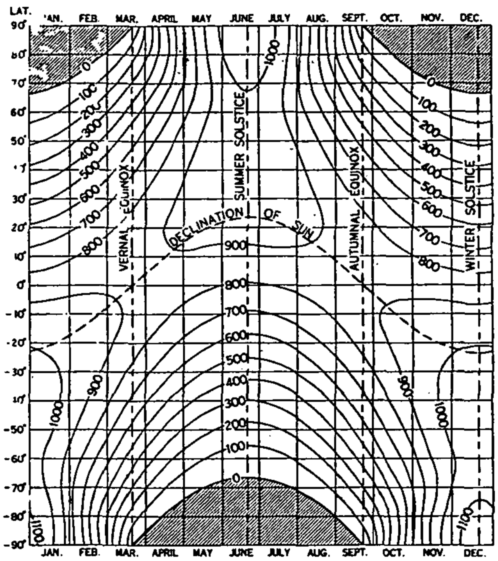


Figure 3.- Total daily solar radiation at top of atmosphere. Solar constant is assumed to be 1.94 cal cm^{-2} min^{-1}. Solid curves represent total daily solar radiation on a horizontal surface at top of atmosphere, measured in cal cm^{-2}. Shaded areas represent regions of continuous darkness. (From The Smithsonian Institution, 1951.)

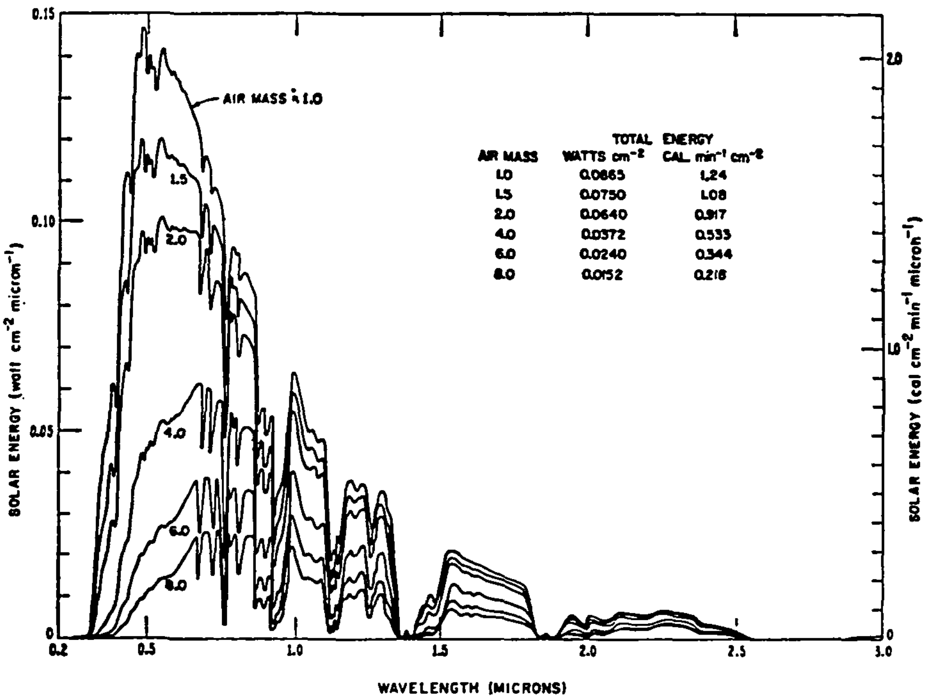
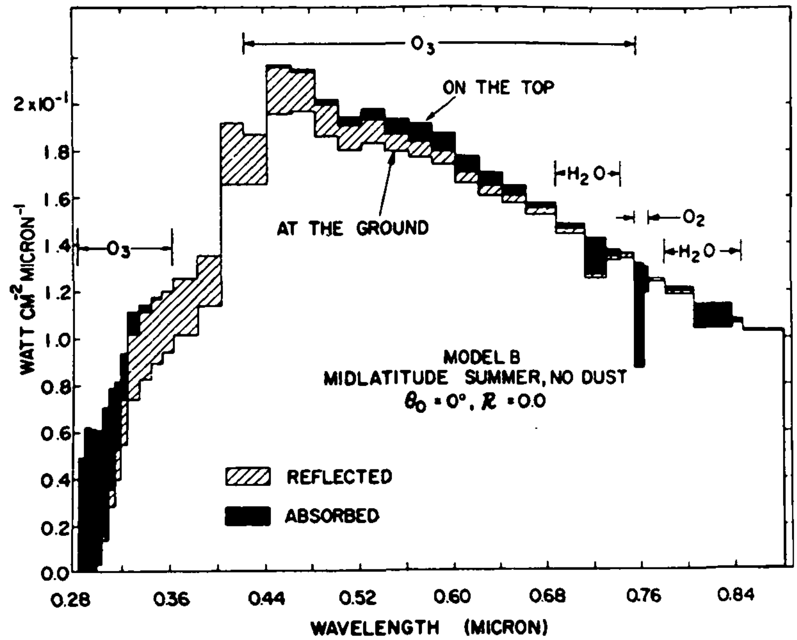
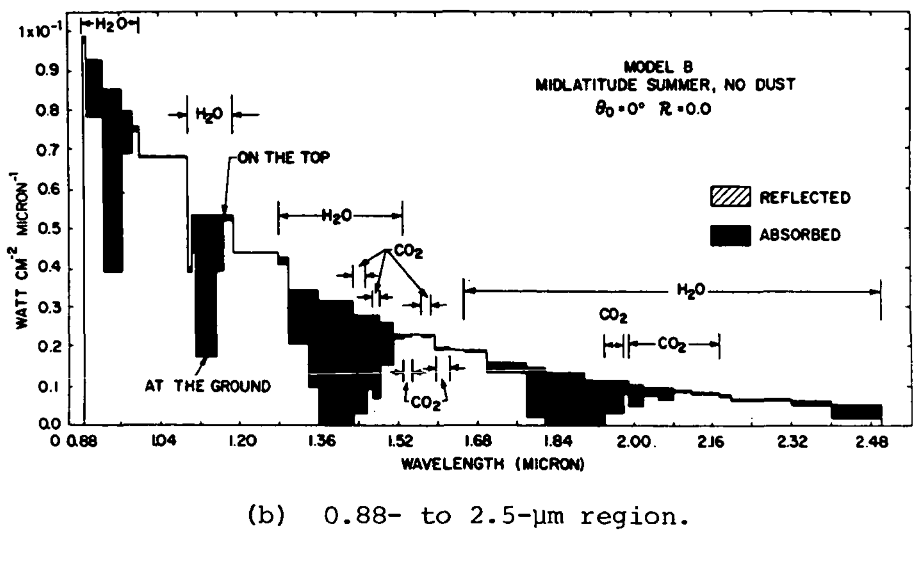


Figure 4.- Spectral distribution as a function of wavelength of direct solar radiation incident at sea level on a surface perpendicular to the Sun's rays for slant paths of air mass 1.0 to 8.0. Concentration of precipitable water = 10 mm, concentration of aerosol = 200 particles/cm^2, concentration of ozone = 0.35 cm. (From Gates, 1966.)



(a) 0.285- to 0.88-μm region.



(b) 0.88- to 2.5-μm region.

Figure 5.- Computed spectral distribution of the 0.285- to 2.5-μm region of the solar flux absorbed within the atmosphere, reflected back to space, and transmitted to a perfectly absorbing ground by a dust-free standard atmosphere, with total ozone of 0.318 cm atm and total water vapor of 2.925 g cm^{-2} in the vertical column of the atmosphere. Sun at zenith. (From Paltridge and Platt, 1976.)

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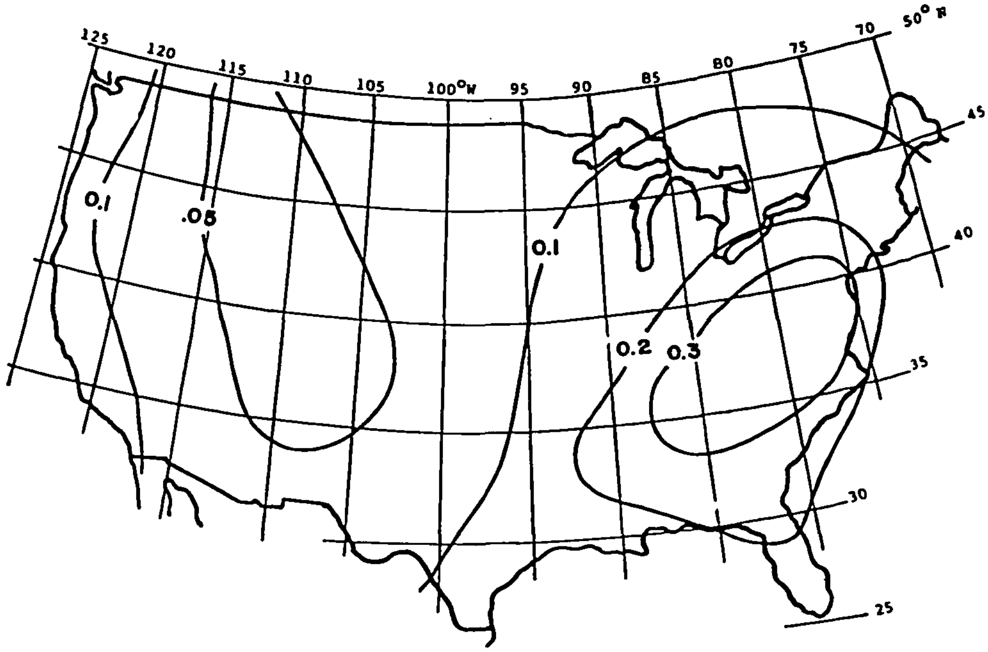

Figure 6.- Atmospheric turbidity over the U.S. in July at 0.5 μm, typical of years 1961 to 1974. (From Flowers et al., 1969.)

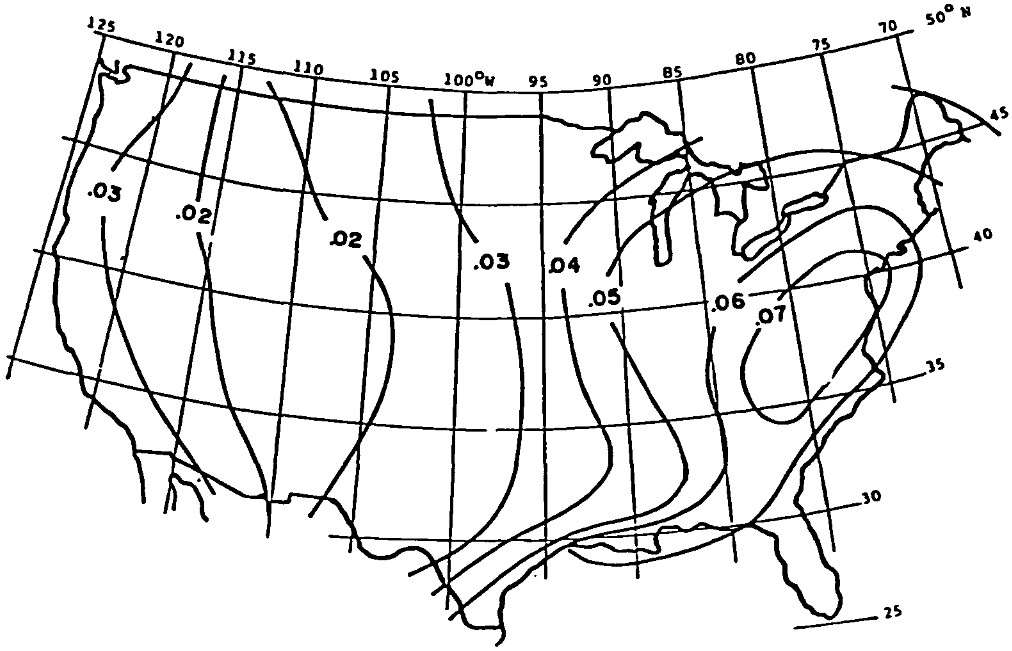

Figure 7.- Atmospheric turbidity over the U.S. in December at 0.5 μm, typical of years 1961 to 1974. (From Flowers et al., 1969.)

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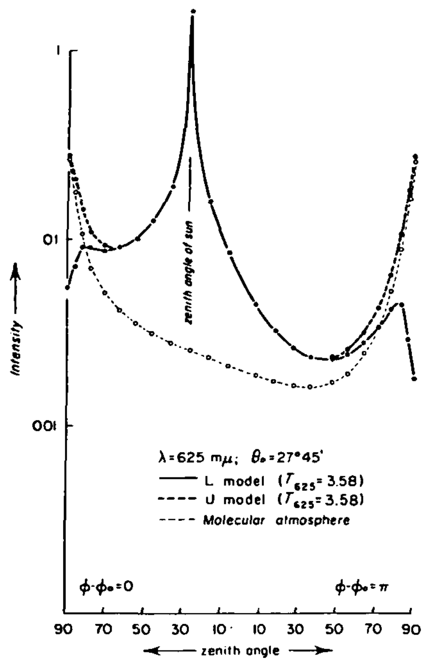

Figure 8.- Relative intensity of skylight in the principal plane for a molecular (Rayleigh) atmosphere and for a turbid layer below (L model) and above (U model) the molecular atmosphere. The Linke turbidity factor is expressed as T. (From Kano, 1964.)

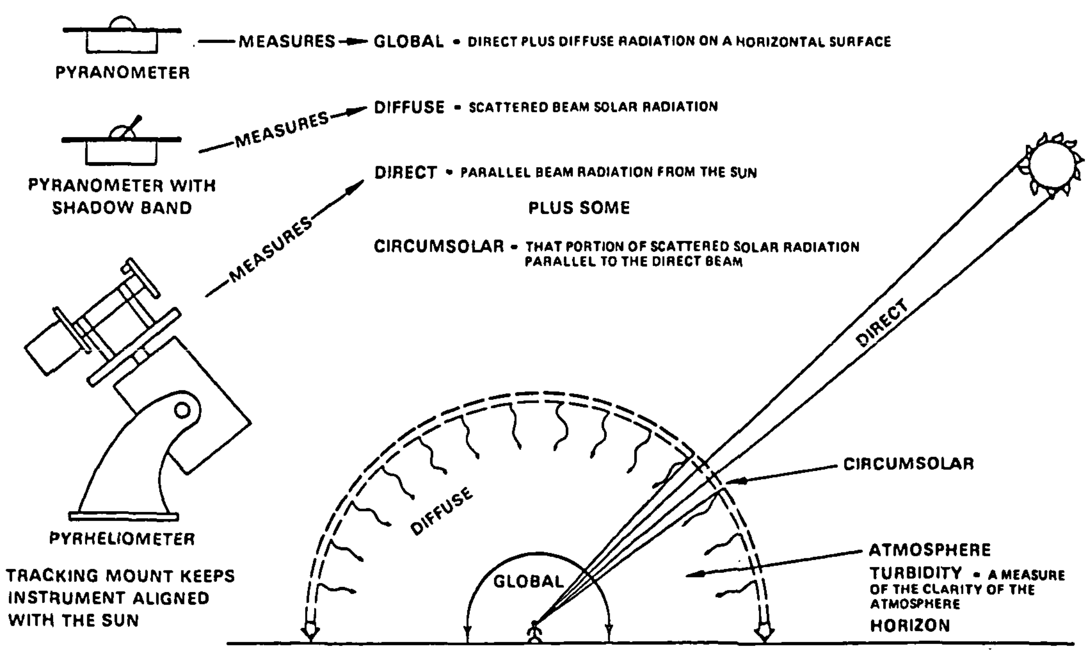

Figure 9.- Types of insolation and measuring instruments.

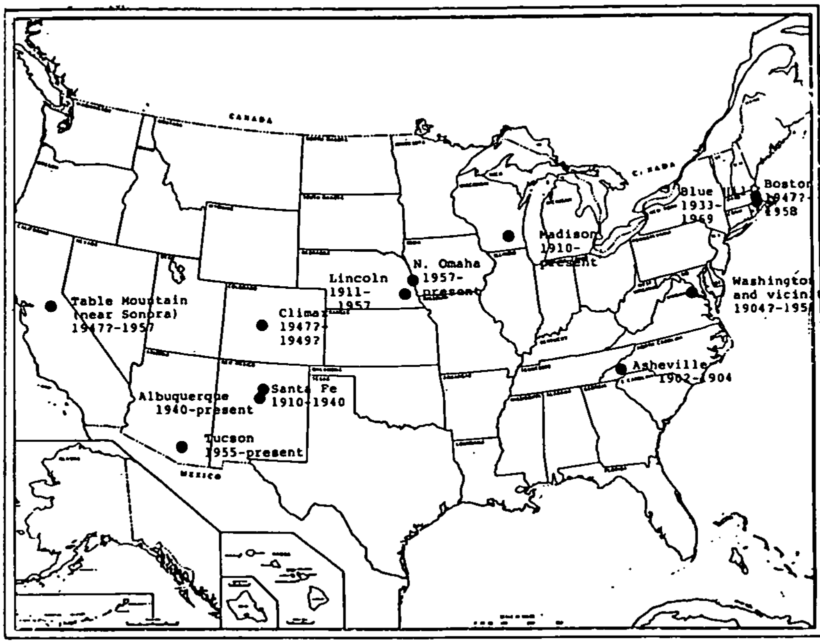

Figure 10.- Locations with normal incidence solar radiation data and period of observations. (After Jessup, 1974.)

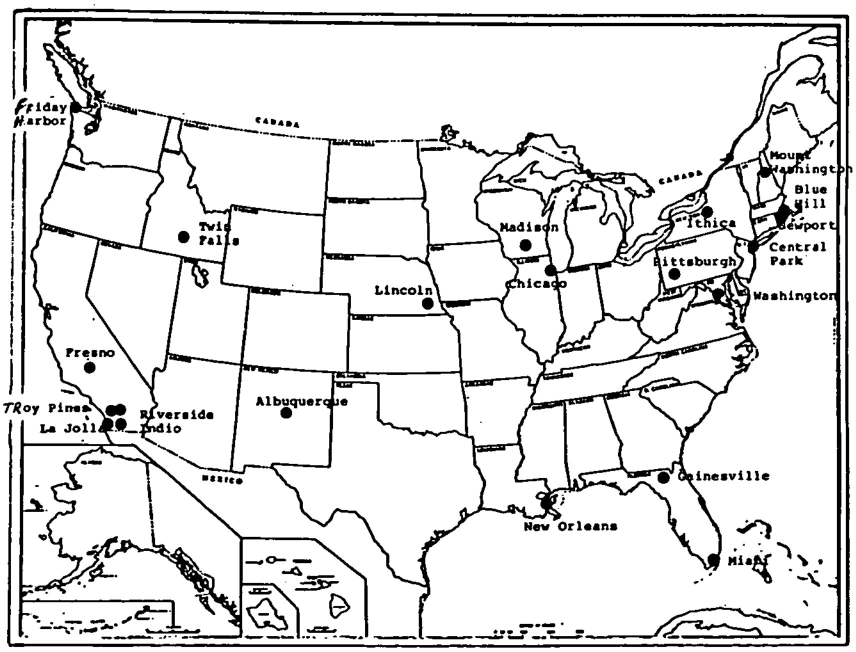

Figure 11.- Solar radiation network, 1939. (After Jessup, 1974.)

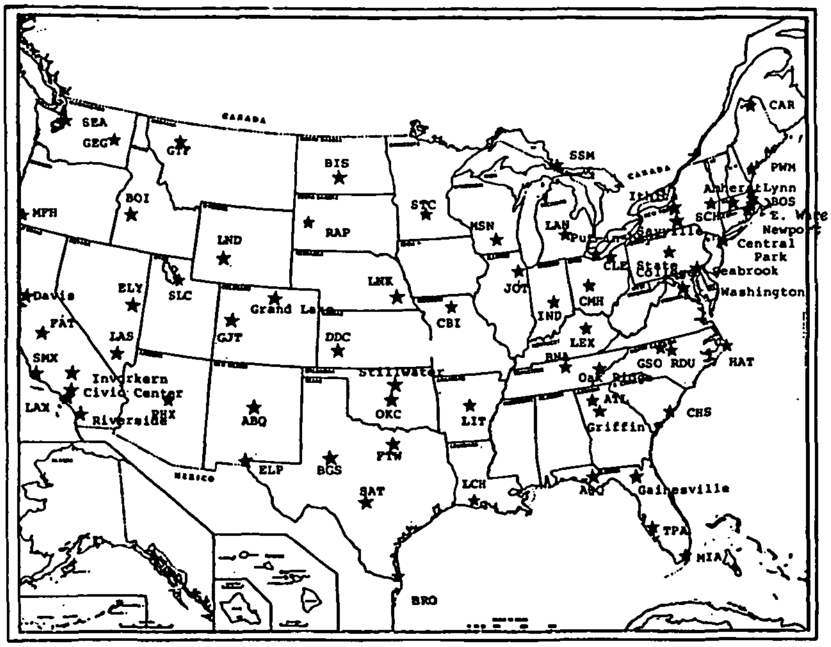

Figure 12.- Solar radiation network, 1951. (After Jessup, 1974.)

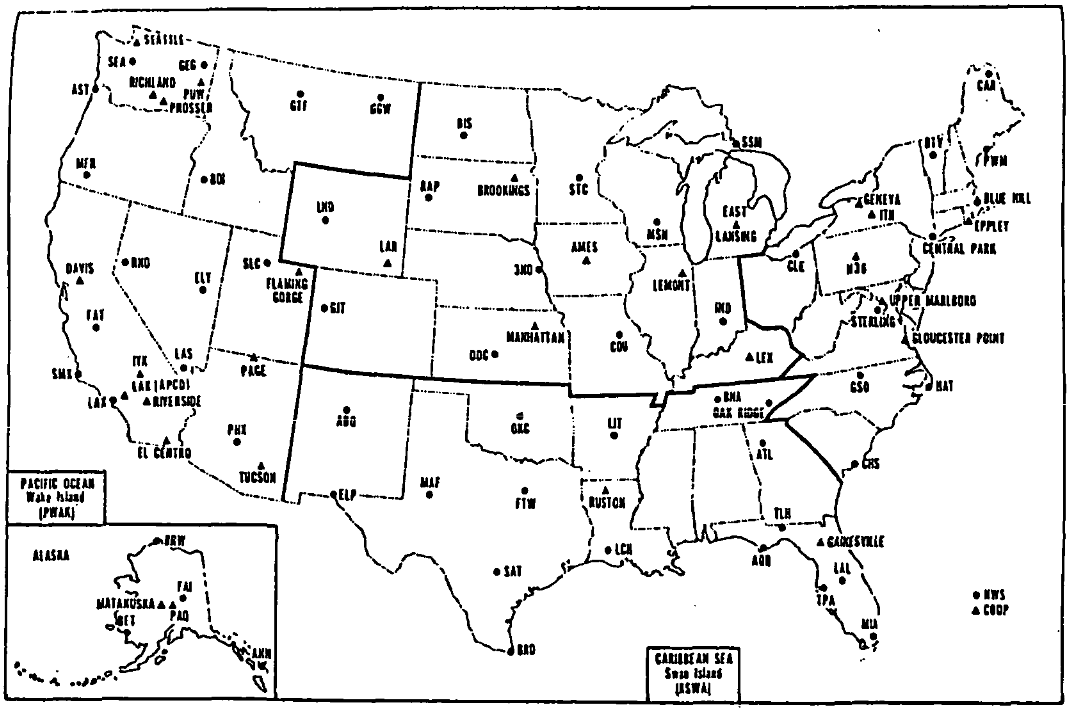

Figure 13.- Solar radiation stations, 1972. (From National Oceanic and Atmospheric Administration, 1972.)

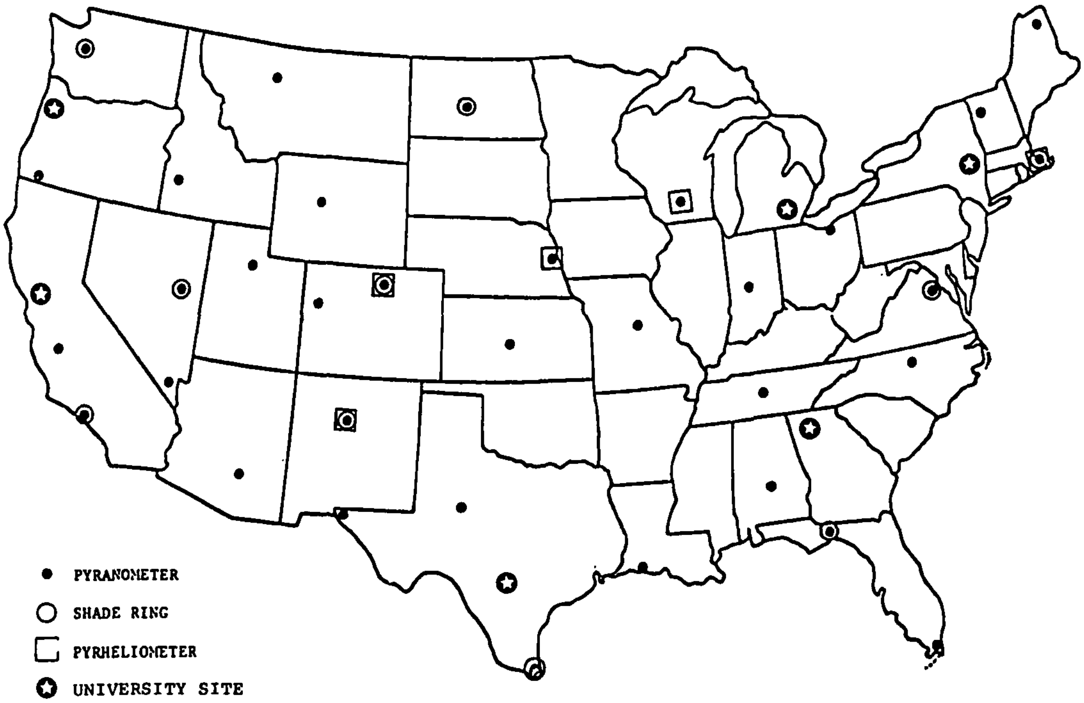

Figure 14.- New National Weather Service solar radiation station network. (Station at Fairbanks, Alaska not indicated.)

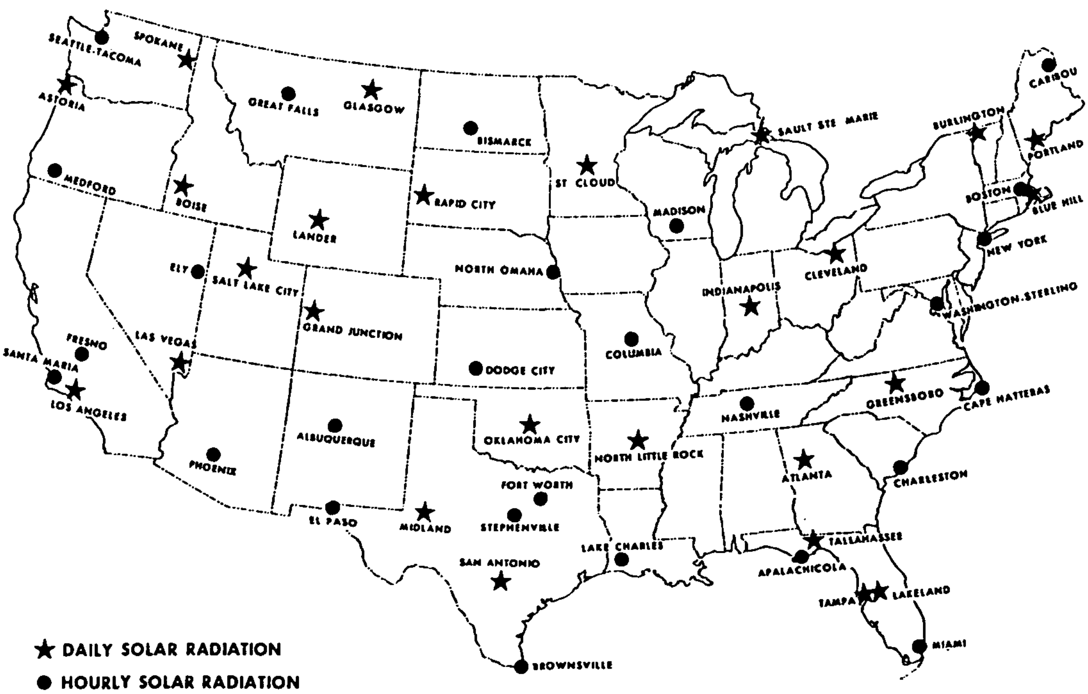

Figure 15.- Solar radiation data rehabilitation stations. (From Carter et al., 1978.)

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Figure 16.- Space Research Building on the University of Michigan North Campus, looking northeast. The table supporting the radiometers is just visible on the uppermost rooftop section.

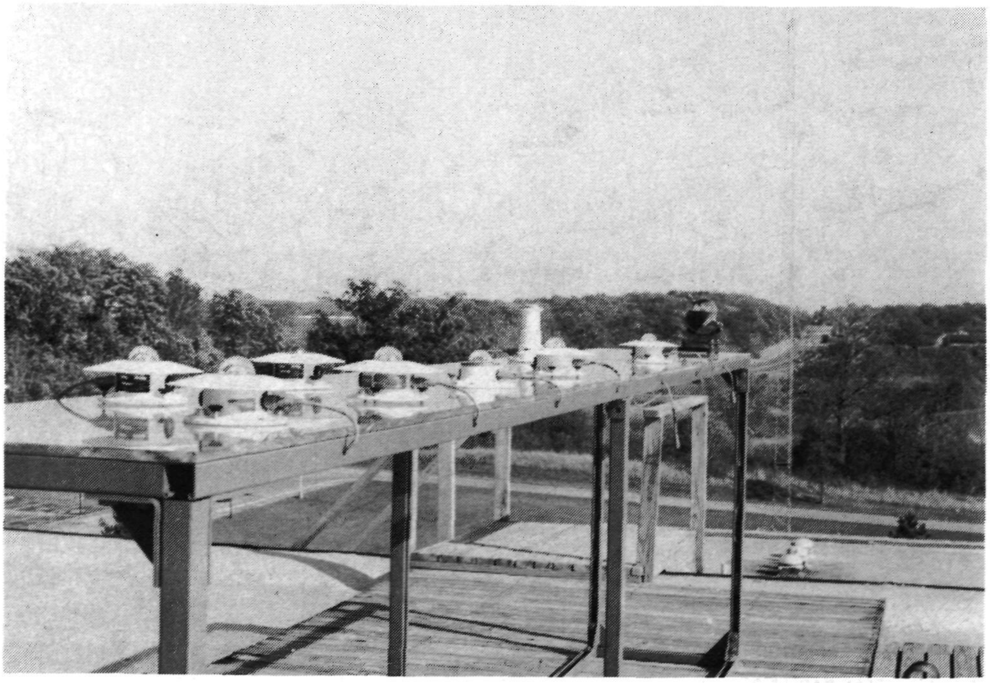

Figure 17.- Main instrument support table with radiometers, looking east-northeast. The 30-m meteorological tower is visible in the background.

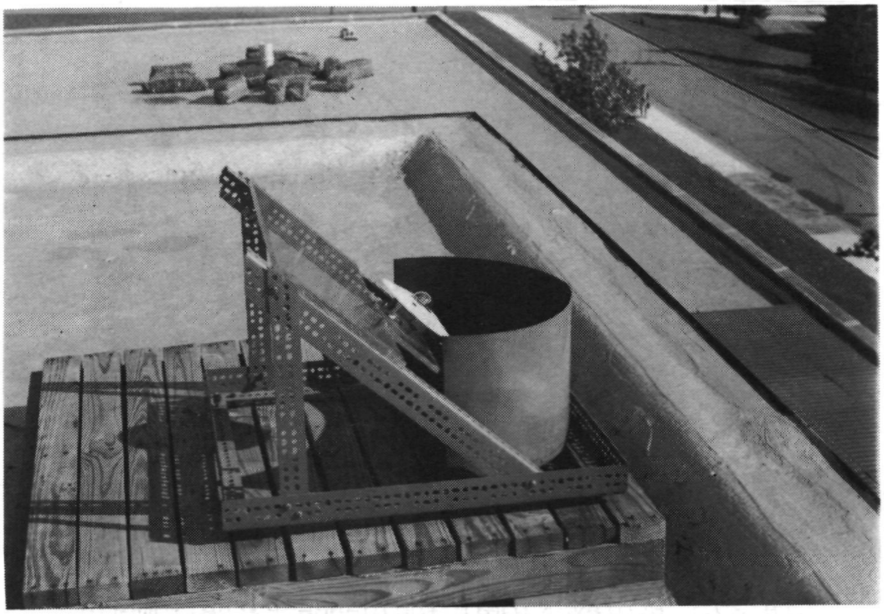

Figure 18.- Eppley PSP tilted at 42.3°-latitude angle and shielded from reflected solar irradiance.

Figure 19.- Eppley PSP shaded by occulting disk for measuring diffuse solar irradiance.

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Figure 20.- Eppley Normal Incidence Pyrheliometer with filter wheel and solar tracker for measuring direct solar irradiance.

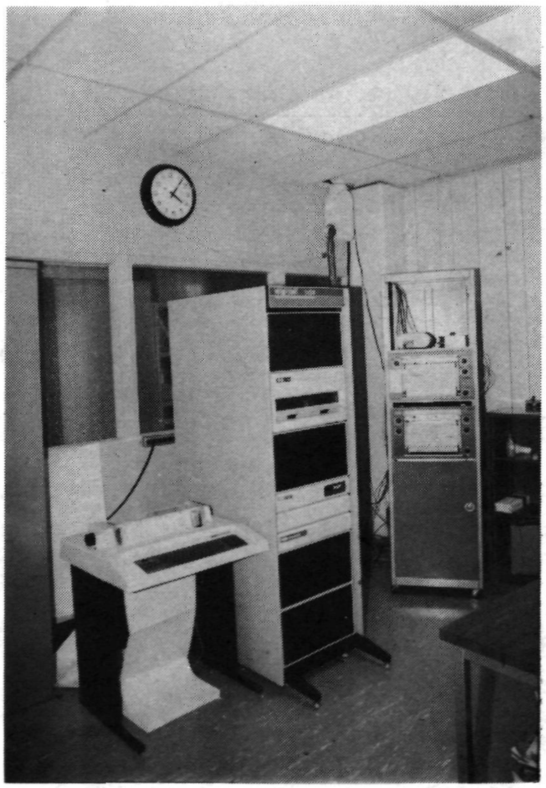

Figure 21.- Analog and digital recording systems - from left to right: typewriter-type terminal, data logging system, and 3- and 4-channel analog recorders.

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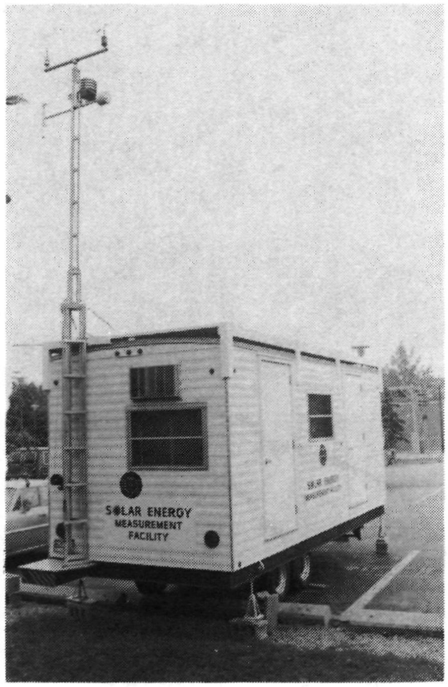

Figure 22.- Mobile measurement facility for solar and meteorological variables.

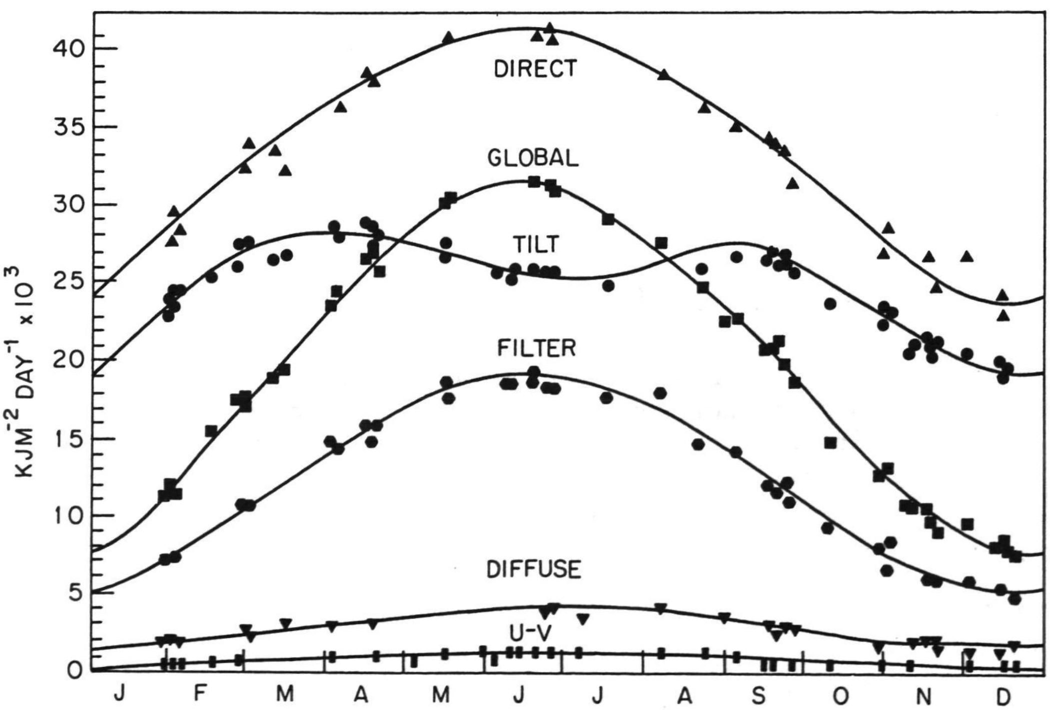

Figure 23.- Measurements of solar radiation taken at University of Michigan SEMRTS sites.

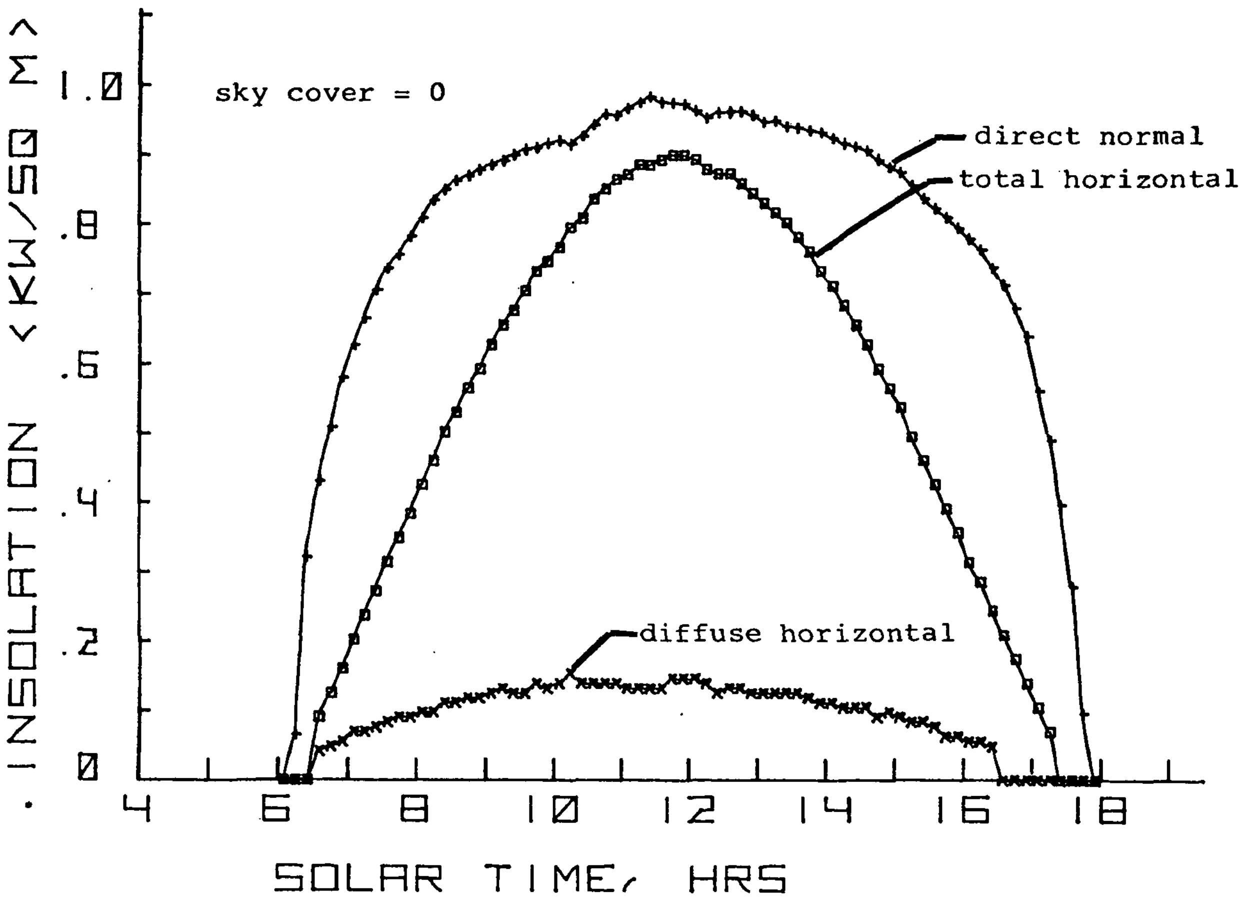

Figure 24.- Diurnal variation of direct normal, diffuse horizontal, and total horizontal insolation. (From U.S. Dept. of Energy, 1978.)

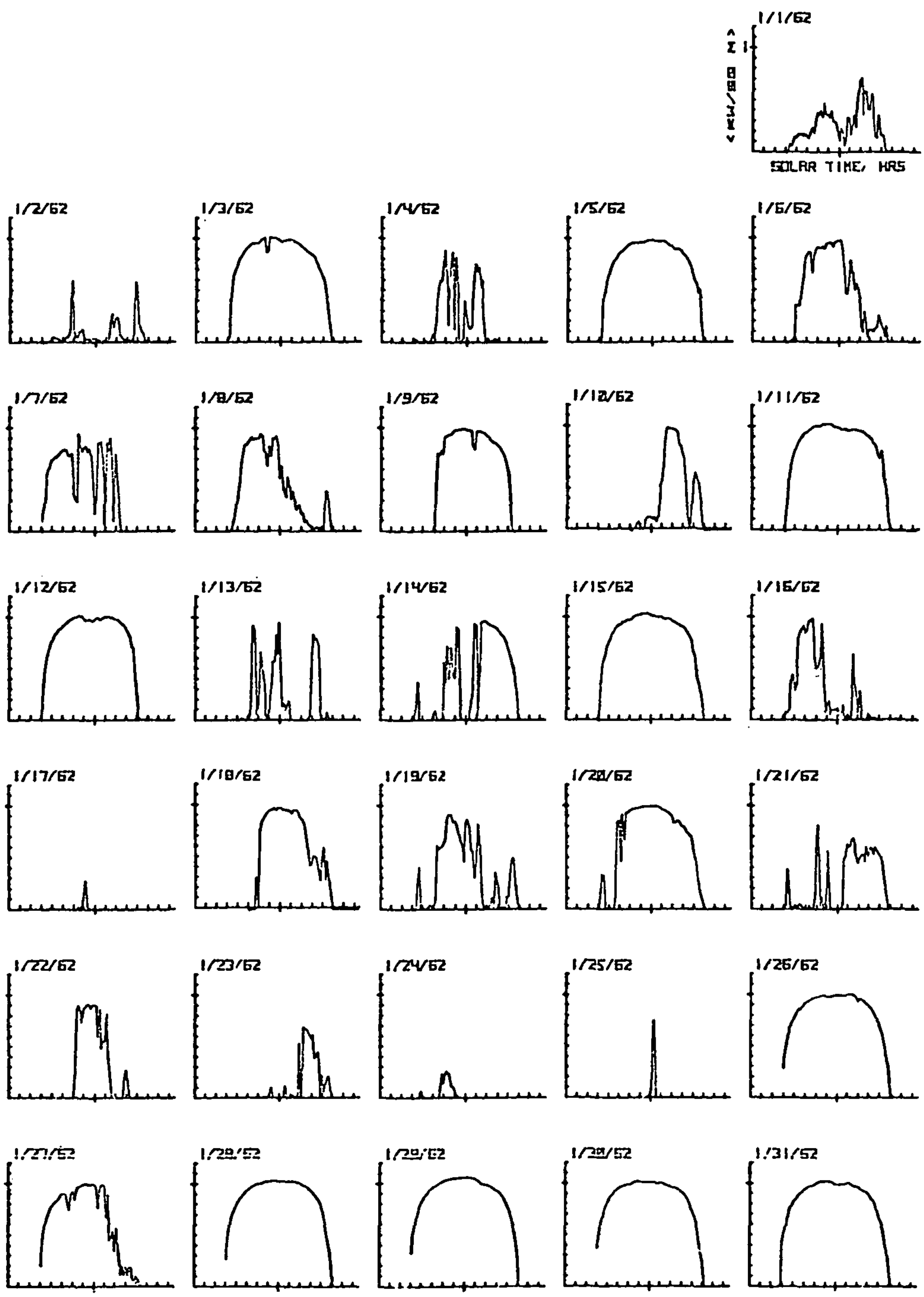

Figure 25.- Direct normal solar radiation for Albequerque, N.M., for January 1962. (From U.S. Dept. of Energy, 1978.)

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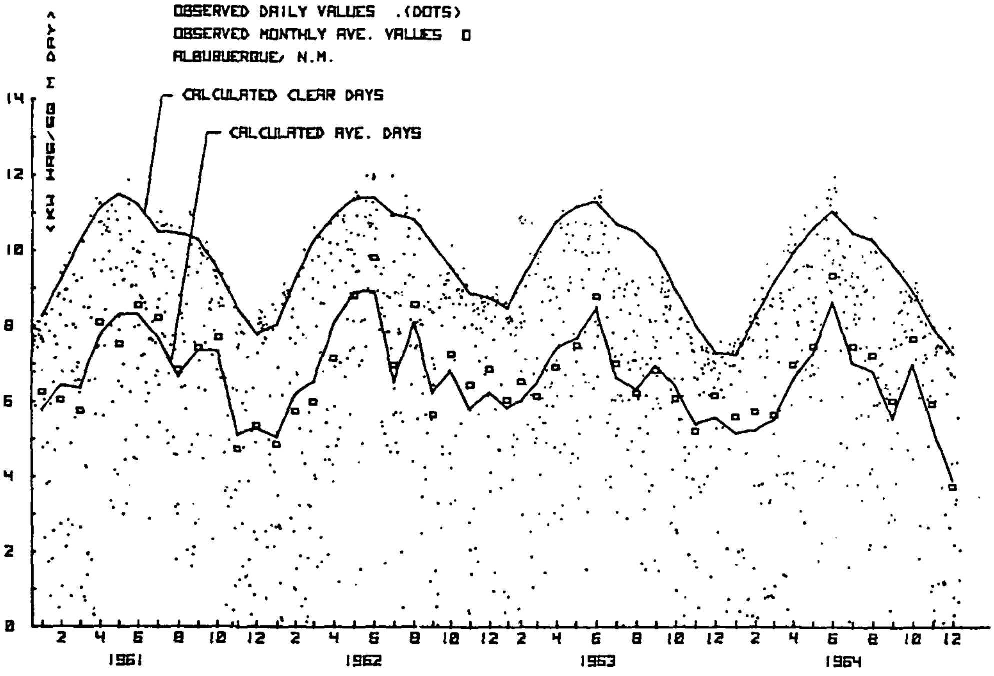

Figure 26.- Direct normal solar radiation for 4-year period at Albequerque, N.M. (From U.S. Dept. of Energy, 1978.)

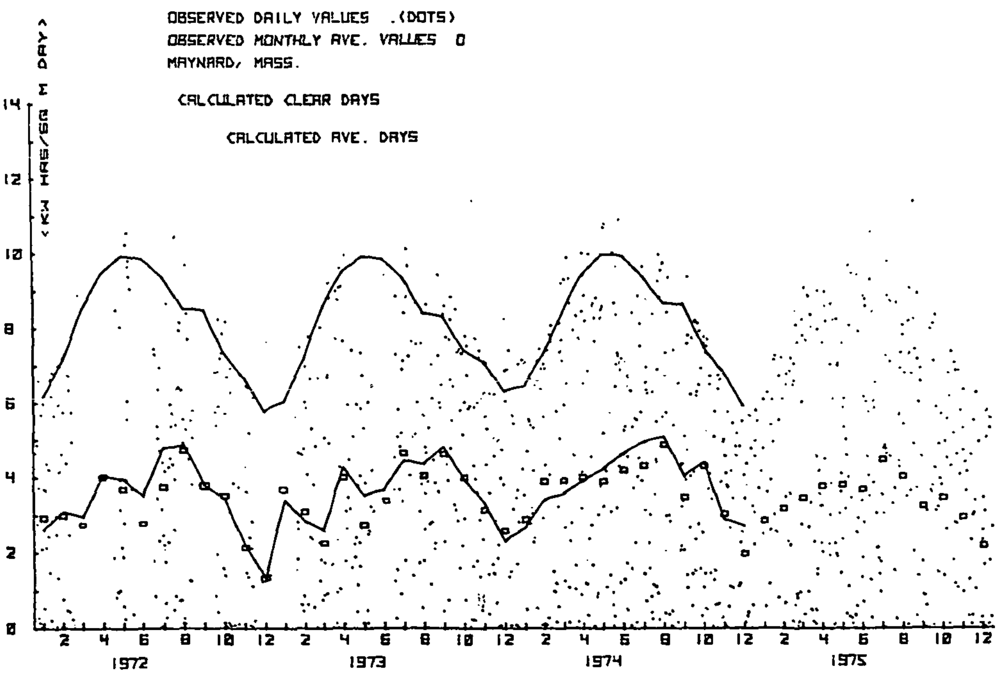

Figure 27.- Direct normal solar radiation for 4-year period at Maynard, Mass. (From U.S. Dept. of Energy, 1978.)

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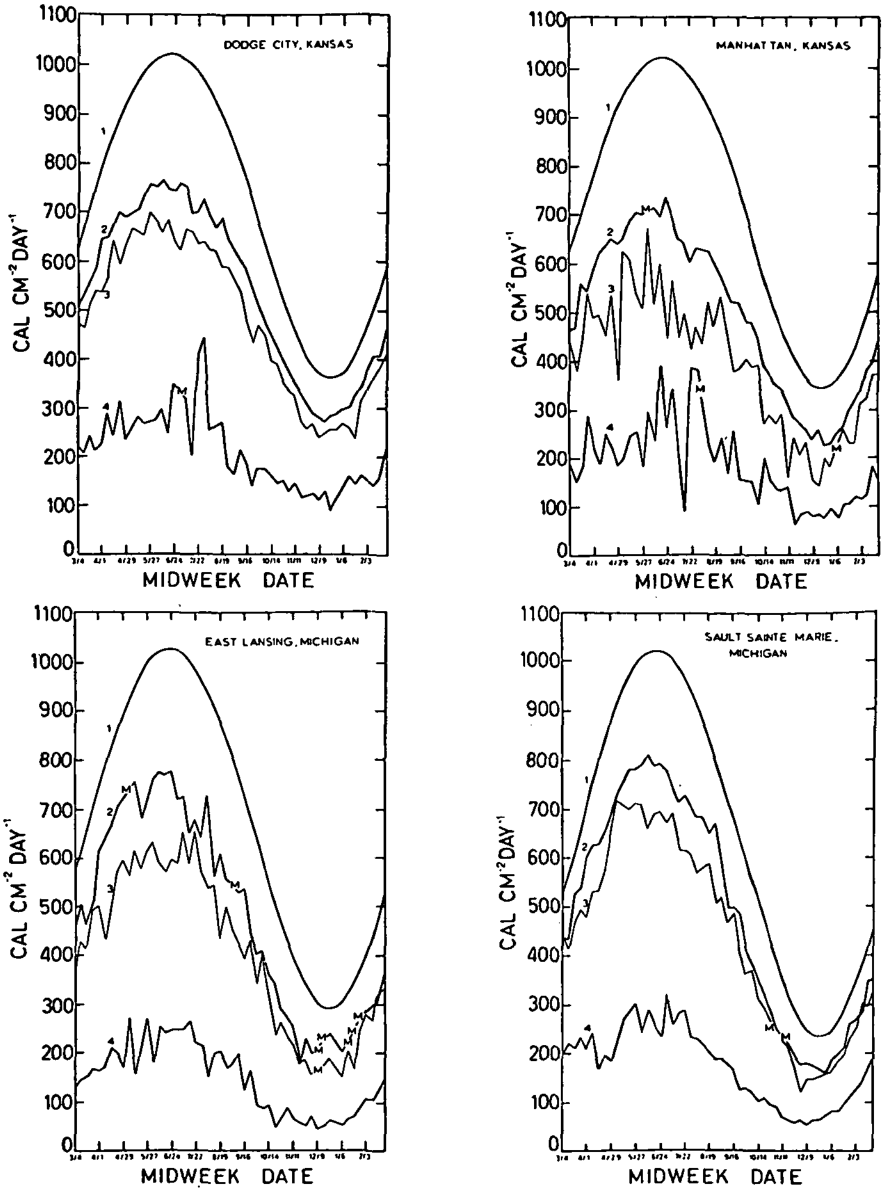


Figure 28.- Calculated total daily extraterrestrial radiation (curve 1) and average measured radiation under clear-sky conditions (curve 2), 50-percent cloud cover (curve 3), and 100-percent cloud cover (curve 4). The symbol M is used when the particular sky condition did not occur during the period of record. Values were plotted at the midweek date of each climatological week. Measured data for Manhattan are estimated to be low by 8.2 percent. (From Baker and Klink, 1975.)

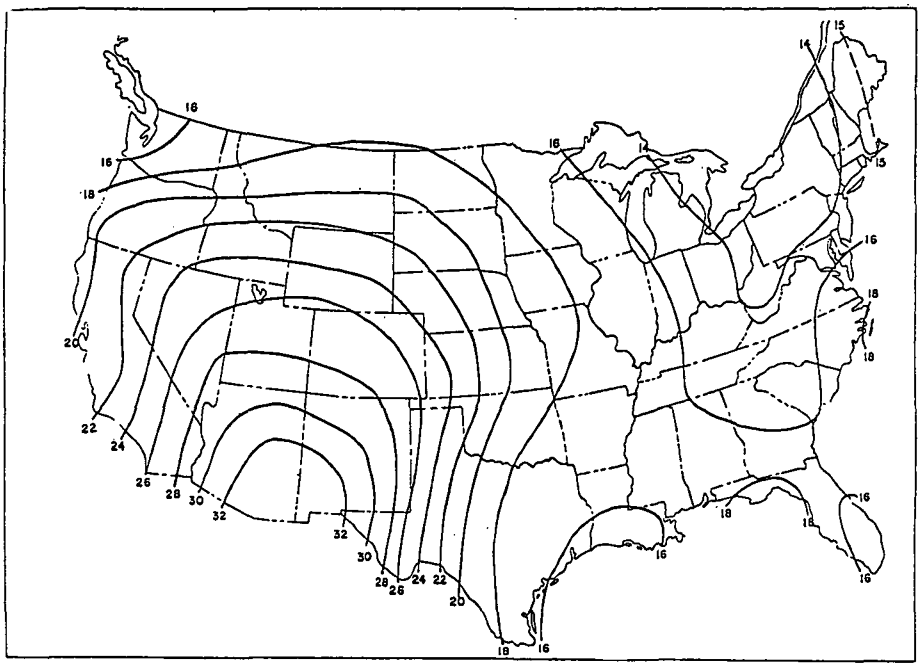


Figure 29.- Mean daily direct solar radiation, MJ/m^2, for May. (Lester Machta, personal communication, Jan. 1979.)

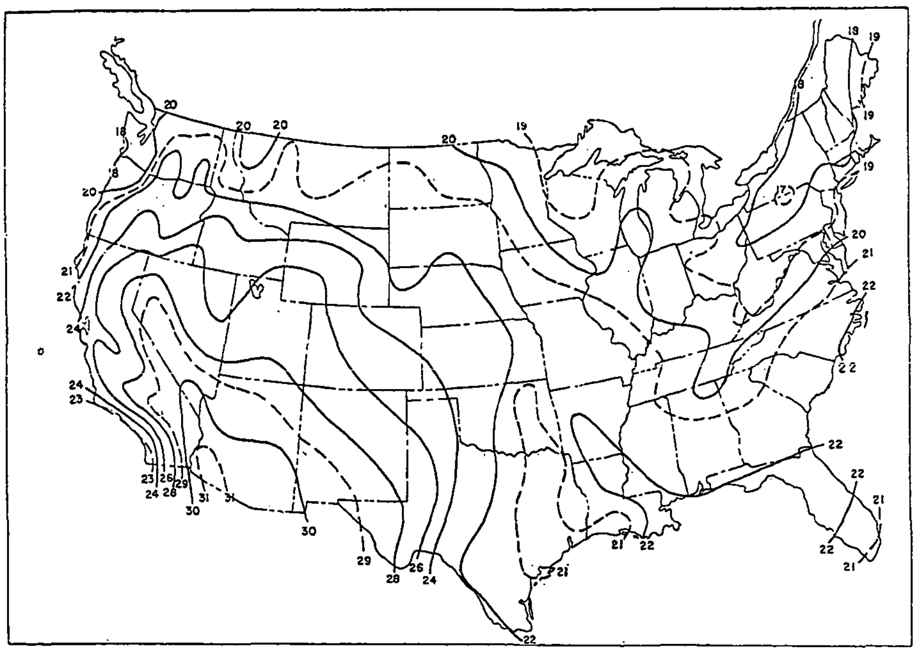
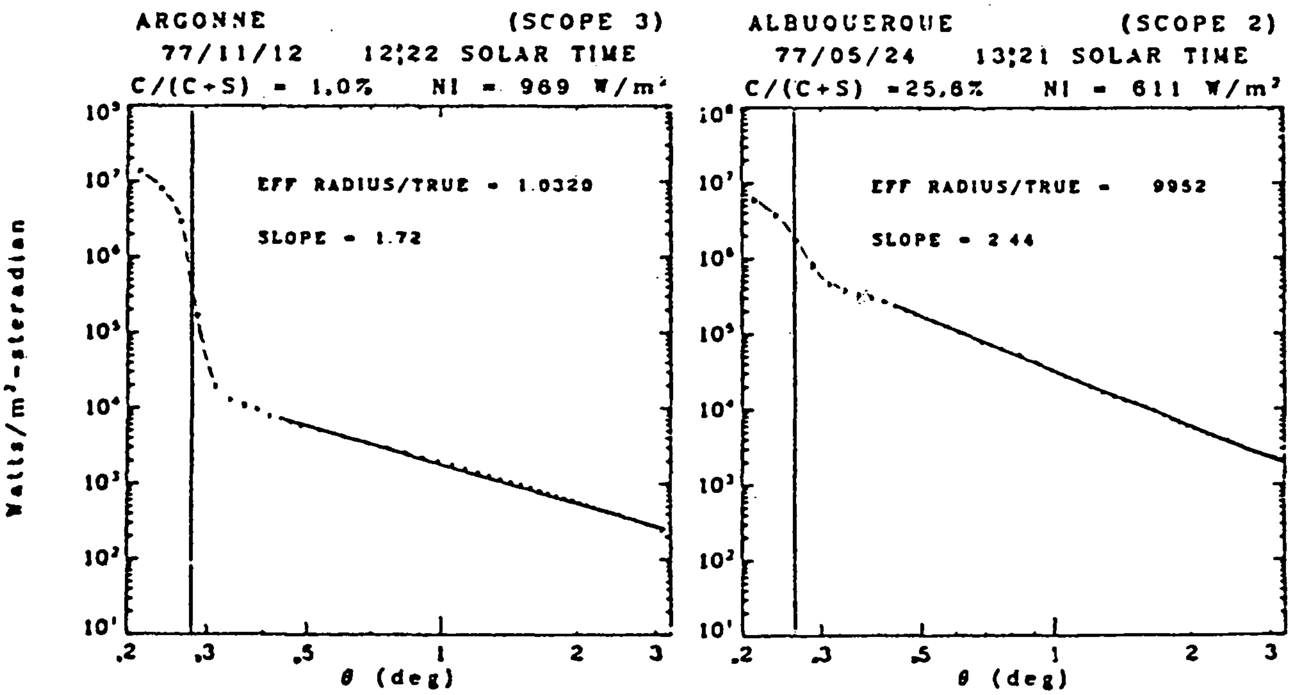


Figure 30.- Mean daily solar radiation on a horizontal surface, MJ/m^2, for May. (Lester Machta, personal communication, Jan. 1979.)



(a) Low turbidity.

(b) High turbidity.

Figure 31.- Effects of turbidity on direct and circumsolar radiation. (From Gregher et al., 1979.)